Empirical and CFD analysis of silica nanofluid using a double pipe heat exchanger

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Abstract

The heat exchangers are widely used in the industrial processes to either heat or cool the working fluids. They prevent the utilization of an external heat source, which highly reduces the cost of production. The Heat exchangers having high thermal conductivity are required to meet the expanding industrial needs. This study targets the enhancement of thermal energy transfer by the usage of nanofluid instead of the conventional fluid such as water, in the concentric tube heat exchanger. The nanofluid was prepared by the usage of silica nanoparticles, having distilled water as the primary fluid. The silica nanoparticles synthesized by green synthesis method are conformed by X-ray Diffraction, zeta potential, FESEM techniques. The hot liquid in the heat exchanger remains unchanged while, the conventional fluid is replaced by the prepared silica nanofluid as cold fluid. In this research, a double pipe heat exchanger is modeled and meshed using ANSYS Fluent 14.5. The heat transmission attributes of silica nanofluid in the equipment are analyzed with the help of fluent software. The amount of nanofluid used for the entire experiment was about 5 l and in order to get a 0.05% volume concentration approximately 7 g of nanoparticles were used. The results of Computational Fluid Dynamic (CFD) analysis and the experimentation were compared and justified. In CFD analysis the cold and hot outlet temperatures are 313.18 and 354.03 K respectively, while the experimental results are 322 and 346 K respectively. An improvement of 10 °C was found in the cooling of the heat exchanger upon the usage of silica nanofluid. The outcome of the present research work, reveals that the addition of nanoparticles to the host fluid leads to significant improvement of thermal properties.

Keywords Silica nanoparticles · Double pipe heat exchanger · Nanofluid · CFD analysis

Nomenclature

mm	Millimeter	T_{ci}	Cold inlet temperature
V_f	Volume fraction	%	Percentage
W_m	Weight of nanoparticle	ε	Rate of dissipation of energy
ρ_m	Density of nanoparticle	ph	Potential of hydrogen
kg	kilograms	W_f	Weight of nanofluid
s	Second	ρ_f	Density of nanofluid
K	Kelvin	g	grams
k	Thermal conductivity	W	Watts
J	Joule	m	meter
nm	nano meter	ρ	DENSITY
T_{hi}	Hot inlet temperature	Cp	Specific heat
		au	astronomical unit

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mV	Milli volts
T_{ho}	Hot outlet temperature
T_{co}	Cold outlet temperature
$^{\circ}\text{C}$	Degree centigrade
k	Turbulent energy

1 Introduction

The industrial sector mainly functions on the usage of thermal energy for their heating and cooling systems. The transmission of heat energy from one channel to another can be done by using a heat exchanger. The medium can be either gas or fluid. The growing industrial demands require a good heat transmission system. For this reason many researches were conducted and in the year 1995, a new fluid was formulated by Choi [1]; in which nano sized flecks were scattered in a host fluid and these liquids were termed as nanofluids. R. L. Hamilton and O. K. Crosser [2]; study introduced the usage of nanofluids to improve the heat transfer properties of fluids. This led to a new field of research which helped to deal with the rapidly increasing industrial demands. Many research works have been conducted using different nanofluids which are synthesized using various nanoparticles (SiO_2 , Al_2O_3 , Ag, Cu, CuO, CeO_2 , MgO, Fe_2O_3 , NiO, Graphene, CNTs, etc.) [3–9] and base fluid materials (water, EG, PEG, etc.).

Researchers Pak and Choi [10], experimentally researched the thermal properties of nanofluid with oxides of both aluminum and titanium as nano particles in the horizontal tube under uneven flow and stable heat flux. It was reported that particles with high conductivity and size are required to improve heat transfer properties. Under the counter flow state, the heat transmission and motion dynamics of titanium oxide nanofluid, having water as the base liquid was experimentally investigated by Duangthongsuk and Wongwises 2009 [11] for horizontal pipe heat exchanger. Their study reported that the inclusion of nano sized flecks to the main fluid resulted in the increment of conductivity and viscosity of nanofluids. The researches [12–18] state that nano fluids have huge advantages like longer stability, low pressure drop and showed an evident increase in the thermal efficiency of the equipment in comparison to the regular fluids.

Khedkar et al. 2012 [19], has researched water and ethylene glycol based fluids having copper oxide nano-sized particles. The final output indicates an increase of 23% in heat transfer for 0.3% concentration. In the study done by Xie et al. 2011 [20], the result state the increment of thermal characteristics by 86% with the usage of ethylene glycol based nanofluids with 5% graphene in comparison to the host fluid. Harris et al. 2006 [21], experimented using Al_2O_3 and CuO nanofluids in laminar or turbulent flow at

different boundary conditions. The results indicated that the Al_2O_3 nanofluids show more enhancement compared with CuO. His study also indicates that heat transfer enhancement by nanofluid depends on factors like increment of thermal conductivity, nanoparticles chaotic movements, fluctuations and interactions. Sharma et al. 2010 [22]; stated that thermal property alter with the change in concentration, i.e., for silver nanofluids with Ethylene Glycol as primary fluid, conductivity increases with increment in ppm of silver.

The study of fluid interactions with another fluid, solid, or gas by the usage of numerical solutions is known as Computational Fluid Dynamic (CFD) analysis. In the CFD analysis, solvers convert the partial differential equations to algebraic equations to solve the equations efficiently. Pendyala et al. [23], in 2015, stated that CFD is a very good medium for learning the thermal and motion properties of liquids in intricate shaped equipment. The CFD investigation done by Ashok et al. [24] in the year 2013, on parallel and counter flow heat exchangers using different nanofluids states that as the cooling water flow increased, so did the amount of heat transfer. With the help of different nanoparticles like SiO_2 , Al_2O_3 and CuO, the forced heat transmission characteristics of fluids are numerically analyzed using a 3D car model, by A. Kamyar et al. [25]. The results obtained indicate that Cu and Al based nanofluids exhibit high thermal properties in comparison to silica nanofluids.

The aim of the present work was to improve the amount of heat transmitted in the double pipe heat exchanger by using silica nanofluid. The silica nano particles were prepared from bamboo leaves by the usage of green synthesis method. The output temperatures of both the cold fluid and hot fluid when nano fluid was used were compared to the usage of distilled water as cold fluid. The validation was done by the usage of CFD analysis for the double pipe heat exchanger using the same specifications and boundary conditions.

2 Experimentation

In the double pipe heat exchanger the nano fluid flows through the inner pipe and the water flows through the outer pipe in counter flow direction resulting in the transfer of heat between the two fluids without any direct contact between them. Bamboo leaves are collected for the synthesis of silica nanoparticles and then the silica nanofluid is prepared. The coolant used in the heat exchanger is a liquid. The CFD analysis is also done using the properties of the synthesized silica nanofluid. Few assumptions are made at the beginning of heat exchanger analysis. The loss

of energy to the circumambience, by the coolant or at the U shaped bends of the pipes is negligible.

2.1 Equipment specifications

The parameters of the experimental apparatus (Fig. 1) are mentioned in Table 1. The outer tube consists of the cold liquid, while the inner tube has hot liquid passing through it. The cold fluid tube, i.e. the outer tube is of galvanized iron. The hot fluid tube is made of copper. The inner pipe should be of a material having high thermal resistance, as the thermal reading of the hot fluid can reach up to 100 °C. The span of the heat exchanger is nearly 1200 mm.

2.2 Synthesis of silica nanoparticles

The silica nanoparticles are prepared through a green synthesis method by using bamboo leaves. Rangaraj et al. 2017 [26] study states the synthesis process of silica nanoparticles. Firstly, the bamboo leaves were cleansed to remove the dust. Later, the dried leaves are powdered and heated in the furnace at 1023 K for 3 h to obtain ash known as bamboo leaf ash. 6N Hydrochloric acid solution was used for the treatment of ash under continuous stirring at 343 K for 1½ h to eradicate the pollutants. The ash acquired was next washed with the help of distilled water until the pH is 7. Under stirring, 2.5N NaOH was added for 2 h at 353 K to get silicate from the ash. Until the pH reaches 2.5, the dropwise addition of sulphuric acid to the supernatant obtained, consists of sodium silicate, was done. The solution then turned transparent. The silica precipitate was rinsed with water to eliminate sodium components. Oven is used to dry the powder attained at 333 K

Table 1 Specifications of heat exchanger

Specifications	Inner pipe (mm)	Outer pipe (mm)
Material	Copper	Galvanized iron
Length	1200	1200
Inner diameter	10.5	21
Outer diameter	12.5	25

for almost 2 days. After 2 h of calcinations at 723 K, the required silica powder was collected.

2.3 Silica nanofluid preparation

The nanofluid was produced by a two-step approach. The prepared silica nanoparticles were dispersed in distilled water, which acts as the primary fluid. The preparation of nanofluids doesn't just involve the addition of nano sized flecks in the host fluid, but must also ensure long lasting dispersion with no chemical disparity of fluid or the nanoparticles. A sonicator or high shear blending device is used to mix nano-powders with base fluids. Regular usage of sonication is needed to reduce particle cluster formation.

$$V_f = \frac{\frac{w_f}{\rho_f}}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}} \quad (1)$$

The amount of nanoparticles added depends upon the concentration of the nanofluid required. Nanofluid was prepared with the desired concentration using Eq. (1) [27]. For, preparation of 0.05% volume concentration of silica nanofluid, 1.325 g of silica nanoparticles prepared was added to the base fluid. Distilled water was taken as

Fig. 1 Experimental apparatus

Fig. 2 Geometry of experimental apparatus

Fig. 3 Meshing of experimental apparatus

a primary liquid. Firstly, the nano sized fragments of silica were measured using the digital weighing machine. Then, they were added to the base liquid in a glass beaker and sonicated using Probe sonicator for 3–4 h. After sonication, a stable nanofluid was obtained.

2.4 CFD analysis of heat exchanger

The CFD analysis has three main phases. In pre-processing, the problem statement is converted to a computer model. Mesh generation and setting the boundary conditions are also done in this phase. The actual computation is done in the solving phase with the help of a solver. Finally, the results obtained are analyzed in the post-processing phase. The modeling of the heat exchanger is done using ANSYS software. The outer pipe consists of silica nanofluid, which acts as the cold fluid. While the inner pipe contains water, which acts as a hot fluid. After modeling the heat exchanger, the meshing process such as face mesh, edge meshing, inflation, etc., are applied. The mesh generated is a polyhedron mesh consisting of 473,012 nodes and 1,287,109 elements. The geometry and meshing of the experimental apparatus are shown in Figs. 2 and 3.

In the CFD analysis, the properties of materials that may be solids, fluids, or gases used need to be specified. Here,

Table 2 Solid properties

Solid properties	Density (ρ) (kg/m ³)	Thermal conductivity (K) (W/m K)	Specific heat (Cp) (J/kg K)
Copper	8980	387.5	380
Iron	7850	344.8	460.54

Table 3 Fluid properties

Fluid properties	Density (ρ) (kg/m ³)	Thermal conductivity (K) (W/m K)	Specific heat (Cp) (J/kg K)
Silica nanofluid	1014	0.63	4105.29
Water	1000	0.59	4179.6

the inner tube material is copper and that of the outer tube is iron. Similarly, the fluids used are water and silica nanofluid. The mass flow rates are also to be specified. For silica nanofluid, the mass flow rate is 0.133 kg/s and for water, 0.027 kg/s. The properties of solids are mentioned in Table 2, while the properties of fluids are in Table 3.

3 Results and discussion

3.1 XRD

The XRD analysis in Fig. 4, confirms the generation of silica nano sized particles from bamboo leaves. The XRD pattern of these nanoparticles designates a characteristic amorphous nature of solids, indicating the lack of crystalline structure. The peak (101) at the position of 22° confirms that silica is amorphous in nature.

3.2 FESEM

The FESEM images of the pure SiO₂ nanoparticles synthesized from bamboo leaves have been shown in Fig. 5a, b with resolution 200 nm and 100 nm respectively. The formation of silica nanoparticles occurs approximately at range 60–250 nm width. They have long rod-like shape and are amorphous in nature.

3.3 Zeta potential

The difference of the potential value of the base fluid and a fluid layer containing ions related to the dispersed particles in the main fluid is known as zeta potential. The potential value obtained for the silica nanofluid in the study is −32.7 mV, which implies the longer stability of silica nanofluid.

Fig. 4 X-Ray diffraction pattern of silica nano-particles **Fig. 5** FESEM images of silica nanoparticles

3.4 Experimental and CFD results

The output temperatures of cold fluid and hot fluid are measured using thermocouples. Different outlet temperatures are obtained when water and nanofluid are used as the cold fluid and the experimental investigation were shown in (Fig. 6). The experimental output is mentioned in Table 4.

The cold and hot outlet temperatures when nanofluid is used are 49 °C and 73 °C respectively. The above results give the heat gradient for the inner pipe as 9 °C for water and 21 °C for silica nanofluid. Similarly, for the outer pipe, it is 13 °C for nanofluid and 4 °C for water. So, there is approximately 10 °C improvement in the cooling of a heat exchanger by the usage of silica nanofluid in place of conventional water.

The CFD analysis is performed for the same heat exchanger using the same experimental heat exchanger design specifications. The CFD analysis results are shown in Table 5. We get the outlet temperature of the hot tube as 354.03 K and the cold tube as 313.18 K. The temperature results are obtained for course, medium and fine meshing of the heat exchanger. The cold outlet temperatures for course, medium and fine mesh are 314.25 K, 312.3 K and 311.21 K respectively. While the hot outlet temperatures for course, medium and fine mesh are 348.33 K, 349.99 K and 350.02 K respectively.

Figure 7 represents that the comparison between the results obtained through experimental results and the CFD results of both the cold fluid and hot fluid. The mesh generated for the heat exchanger is imported into ANSYS Fluent to perform the post processing operation. After importing the mesh, the properties of materials

Fig. 6 Schematic figure of the investigation

Table 4 Experimental results

Hot fluid (°C)				Cold fluid (°C)			
Water		Nanofluid		Water		Nanofluid	
T_{hi}	T_{ho}	T_{hi}	T_{ho}	T_{ci}	T_{co}	T_{ci}	T_{co}
94	85	94	73	36	40	36	49

Table 5 CFD result of experimental apparatus

Temperature of cold fluid (K)		Temperature of hot fluid (K)	
Inlet	Outlet	Inlet	Outlet
309	313.18	367	354.02

Fig. 7 Comparison of experiment and CFD results

and the fluids used in the outer and inner pipe are defined along with the other boundary conditions. The results are obtained after performing number of iterations. Figures 8, 9 and 10 show the temperature, pressure and velocity distributions of the heat exchanger respectively.

Realizable K-epsilon ($k-\epsilon$) turbulence model was used in the CFD analysis with enhanced wall treatment. The TKE, TDR and Energy Prandtl number values are 1, 1.2 and 0.85 respectively. In Fig. 8 it can be clearly observed that the temperature of the inner pipe gets reduced as the fluid travels from inlet to the outlet. Figure 11 shows the residual plot which gives accuracy of the solution. It also helps in determining the convergence of the solution. The animated flow of both the hot and the cold fluid is shown in Fig. 12.

Figures 13 and 14 represent the face plane representation of the inlet and outlets of both the inner and the outer pipes of the double pipe heat exchanger. Figure 13 shows the cold inlet and hot outlet temperature contours while Fig. 14 shows the hot inlet and cold outlet contours of the temperatures. A clear variation in the

Fig. 8 Temperature distribution of experimental apparatus

Fig. 9 Pressure distribution of experimental apparatus

Fig. 10 Velocity distribution of experimental apparatus

Fig. 11 Residual values plot

Fig. 12 Animation representing hot and cold fluid flow

Fig. 13 Cold inlet and hot outlet of heat exchanger

Fig. 14 Hot inlet and cold outlet of heat exchanger

temperature of the hot fluid can be observed from both the figures.

4 Conclusion

In the present study, silica nanofluid prepared by green synthesis process was used in place of conventional fluid. The comparison of the heat transfer was done when both silica nano fluid and water were used to the usage of only water as the inner and outer fluids. The results state that the thermal efficiency was increased by 10 °C, when silica nano fluid was used. The validation for the results is obtained through the experimentation and the CFD analysis. The usage of nano fluids results in the improvement of heat transmission which in turn enhances cooling.

Compliance with ethical standards

Conflict of Interest The authors declare that they have no competing interests

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